TIME TRANSFER TECHNIQUES: HISTORICAL OVERVIEW, CURRENT PRACTICES AND FUTURE CAPABILITIES

by

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ABSTRACT

A brief historical review of time transfer techniques used during the last twenty years will be presented. Methods currently used will be discussed in terms of cost effectiveness as a function of accuracy achievable. Future trends will be discussed in terms of projected timekeeping capabilities.

INTRODUCTION

Within the last 20 years, we have seen improvements of several orders of magnitude in our ability to keep time. This has brought forth a number of sophisticated, timed navigation and communications systems and led to a dramatic improvement in the timekeeping capabilities of many laboratories and observatories. The timekeeping community has always been interested in transferring time between cooperating laboratories and in improving time transfer techniques as timekeeping capabilities improved. Obvious operational economies can be achieved through coordinated and synchronized systems.

Twenty-five years ago, timekeeping at the major observatories and laboratories of the world was between the 25-100 microsecond level. Fifteen years ago, it was at the 5-25 microsecond level. Up to about 5 years ago, it was down to the 1-10 microsecond level. Today, 1 microsecond timekeeping is achievable with a modest amount of effort. In fact, the major timekeeping centers are keeping sub-microsecond level timing, in the 5-200 nanosecond range. Soon, we can expect nanosecond or, even, sub-nanosecond timekeeping. However, it will not be easily achieved or come cheaply.

These statements concerning timekeeping require certain assumptions and understandings. "Timekeeping capability" as used here is neither rigorously defined nor is there a generally accepted consensus on what it means. Some would justifiably say that if they can make sub-nanosecond measurements in a laboratory, they then have sub-nanosecond timekeeping. However, it may not be possible to predict how that time scale will compare with some accepted standard at some future epoch. This view provides the basis for the definition used in this paper. This definition takes into account a "standard" of comparison and includes the duration of the measurement. Therefore, in assessing timekeeping capability for a somewhat realistic case, it should include the ability to maintain a reference clock to within some prescribed tolerance to either a time scale determined by averaging a number of clocks or some external reference over some period of time. In this context, then, a 1 microsecond (us) timekeeping capability would mean that a laboratory could maintain a reference clock to within 1 microsecond of a mathematically derived time scale or some external reference, such as maintained by some navigation system for a reasonable period of time. In order to be concerned with operational systems, a reasonable period of time would be four weeks.

In regard to the earlier mentioned developments in timekeeping, it is obvious that the

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introduction of the commercially available cesium beam frequency standard was a significant milestone which caused the first major improvement noted some 20 years ago. Improvements to the cesium beam frequency standard (improved tube), improvements in the computation of local time scales and improved monitoring and measurement systems contributed to the next two rounds of improvements. During the next 10 years, we can look forward to the introduction of several new devices, such as stored ion frequency standards and optically pumped cesium beam frequency standards, into our timekeeping systems to spearhead the next round of improved capabilities. In order to utilize these devices in a practical way, more robust statistical techniques and improved, more stable measurement systems will also have to be introduced. Table I summarizes in tabular form, while Figure I presents in graphical form the progress made in "timekeeping" over the last 20 years and projects forward an estimate of what can optimistically be expected during the next 10 years.

TIME TRANSFER TECHNIQUES

Very frequently, after a timekeeping system has been inuagurated, it becomes desirable to intercompare it with another system or systems. This desire may be based on real need, such as a requirement to maintain a system to within some specified tolerance, or intellectual curiosity, such as an interest in seeing the performance of one system with respect to another. It should be emphasized that this latter case is also a real need, for example, one can be trying to intercompare laboratory type cesium beam frequency standards as a basis for the definition of the System International (SI) second.

A time transfer comparison is usually achieved by the one or two-way exchange of timing data. One-way time transfer data is based on receiving a timed signal from some transmitting system, such as a satellite disseminating time signal or a navigational system. Usually, one is concerned with simultaneous reception of the same signal. In order to use these signals for precise time transfer, one must first carefully evaluate the propagation path delay from the transmitter and all electronic component delays of equipment used in the receiving system. One usually neglects delays in the transmitting system because all measurements are usually referenced to the time the signals leave the transmitting antenna. However, this does not rule out the need to know the delays through the transmitting equipment. Once the delays have been carefully estimated, they usually remain fixed until components are changed. The received signals are usually referenced to some local time standard. Two-way time transfer depends on the mutual exchange of some timed signals between the two stations involved. Because the mutually exchanged signals travel through the same atmosphere, propagation path delays do not affect the results as they are common to both sets of measurements and usually drop-out of the final comparison of the two-clocks. If there is some relaying device, such as a satellite, between the two stations, then it must be carefully investigated whether each signal suffers the same delay as it propagates through the relaying devices. For satellites, this means careful pre-launch calibration.

Obviously, the precision and accuracy of Time Transfer Techniques should be comparable with the accuracies of the timekeeping capabilities of the systems we are comparing. If not, it could take an inordinately long period of time to make the comparison. A measurement precision of 1 ns will yield a frequency measurement good to 1x10-12 in just 1000 secs (17 min). A measurement system good to 1 microsecond will need over a day to attain the same precision in frequency.

The capabilities and usage of several Time Transfer Techniques over the last two decades will be traced in order to develop a picture of future expectations in the field of Time Transfer. An historical approach to the categorization of the techniques (CCIR, 1982)

will be used. These categories include geographic area of coverage, frequency domain of the technique, and major system categorization, such as, navigation or communications systems.

One of the simplest methods of classification is through the specification of the frequency used to exchange timing data, such as radio or optical. In the former, we usually find sub-groups such as very low frequency (VLF), low frequency (LF), high frequency (HF), very high frequency (VHF) or microwave. Optical methods usually include laser pulses or optical fiber techniques. Various systems developed for special purposes such as navigation or communications can also be used for time transfer. These systems can be either land-based or satellite-based. The most obvious ones are the navigation systems, such as Loran-C, Transit, Omega and the Global Positioning System (GPS) and the communication systems, such as geostationary commercial communications satellites and the Defense Satellite Communications System (DSCS). Very Long Baseline Interferometry (VLBI), because it requires highly precise frequency standards which are used as a local reference oscillator and clock, can be used as a time transfer system over intermediate to intercontinental distances. Time transfer techniques which are local in coverage include both radio (TV, microwave, satellite systems) and optical (laser pulses and optical fibers). Methods which are intermediate in coverage include LF, HF and satellite systems. Hemispheric or intercontinental coverage in time transfer can be achieved through VLF or satellite systems. The latter are used for greatest precision. The satellite systems can be at either radio or optical frequencies.

During the last 20 years, the various systems mentioned above have been used in varying degrees by the timekeeping community to effect time transfers. Some systems have enjoyed more use than others, some have recent popularity. The choice of system is based on requirements and available funding. The popularity of some systems rests on the fact that over the years, they have shown an ability to increase system performance with time and use. Some systems have not and tend to be bounded in their time transfer capabilities. Hence, their usage quickly becomes limited. As it is with timekeeping systems, progress is marked by one of three items:

a) introduction of new devices, i.e. new technique;
b) improvements to fundamentals of technique, i.e. improved propagation theory or hardware;
   or
c) technical improvements in ancillary or support systems, i.e., improved measurement components (SITREM modems).

As the capabilities of these systems for time transfer are traced over the last 20 years, the various factors which have caused enhancements in their capabilities will be mentioned as well as the factors which limit the technique.

RADIO TECHNIQUES FOR TIME TRANSFER

While optical methods, such as the dropping of a time ball at noon, dominated the early history of time transfer, their area of coverage was a limitation to their use. The introduction of the telegraph for time distribution brought about a major revolution in time transfer. The area of coverage of a time transfer system was greatly expanded. A significant increase in accuracy of time transfer was also achieved compared to the dropping of the time ball. We have here the case of an increase in time transfer capability through the use of a new technology.

A. VLF and LF Techniques

In 1904, the use of VLF transmissions from a U. S. Navy communication station for time distribution brought about another revolution in time transfer capabilities. A whole new region of the spectrum and a whole new technology was quickly seized-upon to effect intercontinental time transfer. By 1964 (Blair, 1974), time transfer techniques using VLF transmissions were good to about 50 us. in accuracy. The primary usage of VLF signals which has evolved over the last 20-30 years has been as a means of frequency control and stability measurement. Propagation path variations have proven to be the largest limitation to their use as a source of time. These variations are of a periodic nature, which can be modeled to a large extent, and a non-periodic nature, such as Sudden Ionospheric Disturbances (SID's) and Polar Cap Absorptions (PCA's), whose amounts can not be predicted. It was thought that the introduction of the Omega Navigation System, which used several VLF transmissions, would allow time to be recovered to about 1 us through the use of two-frequency techniques. More will be said about this in a later section. In any event, the non-predictable variations in both the periodic and non-periodic portions of propagation path variations have proven to be a limitation to the use of this technique to better than 10 us in accuracy. Extreme care and ideal laboratory conditions and equipment might reduce this number by 30-60 percent.

LF transmissions are subject to the same limitations in accuracy as the VLF systems. Dispersion, caused by the difference in the phase and group velocities of the VLF and LF waves, must be taken into account. As mentioned earlier, the primary effects in the VLF region are in the ionosphere. While in the LF region, the primary effects are caused by ground conductivity variations.

B. HF Techniques

The HF standard time and frequency transmissions have proven to be the most extensively used timing signals. While unmodelable ionospheric variations tend to limit their accuracy to about 0.2 ms., they are the most widely used and cost-effective means of time transfer. Their lack of great accuracy has not hampered their popularity and frequency of use because there are a large number of users who need time only to the accuracy necessary for everyday life, 1 sec. In fact, these HF signals are necessary for the initially setting most high precision time transfer systems in order to set their observing windows.

C. TV Techniques

While more limited in geographical coverage than other RF techniques, TV time transfer systems are capable of reasonably high degrees of accuracy and precision The original experiment of Tolman et al (1967) and its immediate applications were limited to about 100 ns in accuracy primarily because of receiver noise. Improved hardware has now reduced that number to about 10 ns. The atmosphere now seems to be the limiting factor for this technique. Geographic coverage is limited to primarily line-of-sight by the fact that the path the signals take are subject to large and unpredictable variations in order to compensate for the source of some network programming. Table 2 summarizes the development of the RF techniques for Time Transfer during the last 20 years.

NAVIGATION SYSTEMS FOR TIME TRANSFER

During the last 20 years, navigation systems have been the primary means for time transfer where wide geographic coverage and a relatively high degree of accuracy are required (Klepczynski, 1983). The four major systems in use for this purpose are Omega, Transit, Loran-C, and the Global Positioning System (GPS). In all but the Transit system,

the navigation signals emanating from their respective transmitters are controlled by redundant cesium beam frequency standards. This assures the reliability and stability of the signals.

The importance of these navigation systems to the timekeeping community cannot be overstated. Loran-C has been the primary vehicle which has allowed the Bureau International de l'Heure (BIH) to compute International Atomic Time (TAI) based on international representation. By noting the difference of contributing cesium clocks with respect to locally received Loran-C signals, it is possible to form a semi-global time scale through somewhat sophisticated averaging techniques (Granveaud and Guinot, 1976). The degree to which the various Loran-C chains can be coordinated (Charron, 1981) determines the geographic extent of contributing laboratories. The use of GPS for this purpose has been growing. Because of its precision and accuracy and because it is a truly global system, GPS can contribute significantly to this task. In fact, GPS timing receivers are now located on four continents and are allowing many more laboratories to contribute to the formation of TAI. It is thus becoming a truly international time scale.

A. Omega

As mentioned earlier, Omega suffers from the same limitations that affect all VLF transmissions. Initial experiments with dual frequency timing receivers indicated that it was possible to build a receiver that could acheive a microsecond precision in timing. Unfortunately, ionospheric variations significantly degraded the transmitted signals to the 1-5 us level. More significantly, the frequency difference used in the experimental dual frequency timing receivers was not found among the frequencies actually transmitted by the operational Omega system, including the four navigation and one unique frequency transmitted by each member of the system. Thus, while Table 3 indicates a limit of 5 us for Omega time transfer, it cannot be achieved in practice.

B. Transit

The navigation solution in the Transit system analyzes the received Doppler shift of the signal transmitted from the spacecraft. The stability requirements of the transmitted navigation frequency translates into a timing requirement of about 500 us. These requirements can be met by a high quality crystal oscillator. However, the ground stations which control the spacecraft oscillator, all make their measurements with respect to cesium beam frequency standards. Thus, control of the spacecraft oscillator is operationally maintained at a higher level than required by the navigation requirements. In fact, Transit timing receivers can attain a precision of 25 us in their time transfer capabilities. The new Nova satellite, which was launched into orbit in 1982, contains a significantly better oscillator control system than the older Oscar satellites, consequently time transfers utilizing the Nova spacecraft can achieve a precision of between 3-20 us. In addition, the Nova spacecraft has built into it a PRN code modulation scheme which has the inherent capability to improve Transit time transfers to the sub-microsecond level. Unfortunately, this capability has not been operationally implemented.

C. Loran-C

Each of the 3-5 transmitting sites making up the stations of a Loran-C chain has 4 cesium beam frequency standards governing the timing of the transmitted pulse. Synchronization within a chain can be kept within 20 ns. However, this is a relative synchronization and relates to navigation. It does not pertain to time transfer accuracy. It is a measure of the ultimate accuracy limit for time transfers if all

systematic effects can be taken into account. The initial time transfer receivers developed for Loran-C were very awkward to use, requiring an oscilliscope and excellent judgement in locating the third zero crossover of the first pulse of the series of navigation pulses. The early seventies saw the emergence of the Austron 2000C Loran-C timing receiver. While it was not a completely automatic receiver and still a little cumbersome to use, it did help make the process of locking the receiver to the Loran-C signals a little easier. A good technician, with a little training, could set one up within an hour. However, the process still required the use of an oscilloscope and good judgment in locating the third zero crossover.

Our knowledge of the perplexities of the propagation path delay computations has improved. Computer programs, which computed the propagation path delay, began to take into account the conductivity of the surface over which the signals travelled. Thus, it became possible to achieve microsecond time transfers using Loran-C in certain parts of the world. With the advent of the Austron 2100, a microprocessor based Loran-C timing receiver in the early 80's, many of the problems associated with setting up a Loran-C timing receiver disappeared. The primary one being the selection of the third zero crossover. Inspection of time transfer data taken with these new receivers indicate a root mean square error of about 20-30 ns. Unfortunately, comparison of Loran-C time transfers with other techniques, in particular communication satellite time transfers (Costain et al, 1979) are supporting the conjectures that there is an annual variation in the propagation path delays on the order of about 1 us.

D. GPS

The GPS system is a satellite-based navigation system which will give 24 hour, world-wide, three dimensional position fixing capability to two levels of accuracy, 16m and 100m, respectively. The navigation signals transmitted from each of the 18 satellites in the final configuration will be controlled by cesium beam frequency standards or a rubidium frequency standard. GPS system time, which is based on the time kept at a ground station which has been designated as the master clock for the system, is physically kept to within 1 us of UTC(USNO). In addition, a set of coefficients is transmitted with the navigation message which allows the user to derive UTC(USNO) to within 100 ns.

Two portable clock verification trips in the mid-seventies showed that the GPS system would prove to be the major time distribution and time transfer system of the future. The first involved the acceptance testing of a single frequency time transfer unit (Putkovich, 1979) which showed that the set was capable of an accuracy of 50 ns. The second verified the time transfer capabilities of a specially modified dual frequency navigation receiver (Roth et al, 1979). This series of experiments showed an accuracy of 27 ns in time transfer capability. That these tests verified the time transfer capabilities of the GPS system at such an early stage of its development, indicated that the system had great potential.

Allan and Weiss (1980) pointed out the advantages of using common-view time transfer measurements. In this way, the limitations in precision of present single frequency GPS Time Transfer Units can be better overcome. By looking at the same satellite at the same instant, two stations could reduce the error budget in their time transfers by a significant amount because all errors common to the spacecraft clock and most of the error due to poor ephemerides would be eliminated from the measurements. The primary errors left in the measurements would be that due to the differential, unmodelled ionospheric path delays between the two stations. The differential unmodelled tropospheric corrections should be about a nanosecond or smaller, provided that the

tropospheric models are correct. Portable clock visits, which are also necessary for system calibration, have demonstrated that common-view GPS time transfers show a consistency of between 5-10 ns. Table 3 summarizes the development of navigation systems for Time Transfer during the last 20 years.

SATELLITE SYSTEMS FOR TIME TRANSFER

Besides the satellite-based navigation systems, there exist a number of satellite-based communications systems which are extremely effective for time transfer. The use of geostationary communication satellites for time transfer goes back to 1962 when clocks at USNO, NPL and RGO were compared to an accuracy of 1 us using two-way exchange of 5 us long pulses through the Telstar satellite (Steele et al, 1964). During the late 70's, a three-year long link was established between North America and Europe using the Symphonie satellite (Costain et al, 1979) at C-band (4/6 GHz). At the same time, experiments using the Hermes/CTS satellite at K-band (12/14 GHz) were commenced between USNO, NBS and NRC (Costain, 1979). Sub-nanosecond precision and accuracies of 20-50 ns were obtained by these techniques. Recently, a new PRN modem (SITREM), specially designed for time transfer (Hartl et al, 1983 a), has been used in some experiments (Hartl et al, 1983 b). While precisions in time transfer achieved with this PRN modem are comparable to those achieved in the latter Hermes/CTS experiments, i.e., 600 ps, the main advantage of these modems lies in their simplicity of use and small power requirements. Only 1 watt of transmitting power is required. Because of the PRN coding technique and low power, the signals are non-interfering.

If care is not taken to carefully calibrate and measure all delays in the satellite being used before launch, these techniques suffer in attainable accuracy. Hence, portable clock trips are necessary to remove systematic errors between cooperating stations. Because these techniques use two-way exchange of signals, many common errors drop out of the time transfer mathematics. However, non-reciprocal delays through the channels and transponders of the satellite do not drop out, as well as differential ionospheric and tropospheric delays. The use of DSCS for time transfer is similar to that of using commercial communications satellites, in principle. Because of operational requirements, there are some technical differences in how the time transfers are made. However, the results are comparable.

The GOES satellite is primarily a weather and environmental monitoring platform. The data down-linked from the satellite contains a time code provided by and referenced to the NBS (Hanson et al, 1979). The system is used as a time distribution system in North America. If the user applies corrections for his location, an accuracy of 1 ms can be attained. If the user also applies corrections for the position of the satellite, an accuracy of 30-50 us can be achieved. Table 4 compares the capabilities of some satellite systems over the last 20 years.

SPECIAL SYSTEMS FOR TIME TRANSFER

While navigation and communication systems are significant contributors to the timekeeping field, several other systems, such as VLBI, laser ranging and Portable Clocks, also contribute significantly. There is no single unifying theme which brings these three techniques under one category. VLBI requires highly precise frequency standards at each station in a network. The VLBI correlation process, itself, determines the offsets in both epoch and frequency of the clocks within the network. Thus, a VLBI network is a self-contained synchronized network (but not in real-time). Very short laser pulses can form the basis of a highly precise time transfer system, because the time of arrival of a coded sequence of extremely short laser pulses can be unambiguously and

precisely determined. Portable clocks are included in this category because they have been the ultimate technique for verification and calibration of all other techniques. VLBI has shown itself to be an extremely precise time transfer system. Over the years, the data recording techniques used in various VLBI systems has grown and evolved into the present wide band system known as the Mark III system. The original Mark I sytem had a bandwidth of only 2 KHz. Allen Rogers (1976) has shown that the ultimate capability to synchronize two VLBI tapes is based on their bandwidth and S/N ratio of the observed sources. For the Mark I system, this is about 150 ps. For the Mark II system, whose bandwidth is 4 MHz, this number is typically about 100 ps. These numbers refer to the inherent precision which the correlation process can attain. However, there are many systematic effects which must be removed in order to achieve accuracy. Several experiments have attempted to verify the VLBI intrinsic capabilities by carefully calibrating and evaluating the many delays through the elements of a VLBI system (Clark et al, 1979; Spencer et al, 1981; and Johnston et al, 1983). The best results which have been obtained to date are those of Spencer et al (1981) and Johnston et al (1983) where verification was done at the 3 ns and 2 ns levels, respectively. It has become rather obvious that at these levels, present day verification and calibration techniques are marginally adequate. The ultimate limitation to VLBI time transfer appears to be the atmosphere and will limit the accuracy of VLBI time transfers to about 60 ps (Crane, 1976).

The two-way exchange of laser pulses should prove to be an extremely precise and accurate method for time transfer. When used to synchronize two ground stations over a distance of 35 km, a precision of 600 ps was achieved (Alley et al, 1982). Intercontinental time transfer, as proposed by the Lasso Program (Leschiutta, 1979), using a satellite with a retro-reflector and an on-board event timer should achieve similar results. However, this experiment has not been done as yet because the satellite planned for this purpose never made it into orbit. Use of very short laser pulses assures that the time of reception will be precisely recorded. Use of a reflecting surface, as opposed to a relaying transponder in the radio region, assures a reciprocal path. The differential variations in the propagation path delay during two-way exchange of laser pulses would become the limiting factor to the accuracy of this method. Thus, it seems that this technique should prove to be the verification and calibration system of the future. Unfortunately, laser stations which have sufficient capability both in regards to manpower and equipment are very few and very expensive to operate.

For the moment, the portable clock is the primary, although somewhat limited, verification and calibration system for certifying the accuracy of time transfers. Over the years, the capabilities of portable clock trips has improved. Initially, in the early 60's, one could only expect 1-5 us as the resulting accuracy of a PC trip. This improved dramatically with the introduction of the cesium clocks with the high performance beam tube. Since the early 70's (Putkovich, 1981), several factors have contributed to the further improvement in the accuracy attained with PC trips. Improved monitoring of the PC before and after the trip and care in minimizing the duration of the trip have helped the situation. For special critical experiments, an ensemble of clocks (Hafele & Keating, 1972 and Spencer et al, 1981) has been used. Presently, the best performance that can be expected from a PC trip is about 1 ns. This means a short trip and use of more than one PC. Table 5 shows the capabilities of these special systems during the last 20 years.

COST FACTORS OF VARIOUS TIME TRANFER TECHNIQUES

Many factors enter into the choice of selecting a time transfer system to meet a requirement. Very often, cost is the single most important factor. Table 6 is presented in order to give a comparison of costs versus accuracy of technique. There is a general trend of

increased precision meaning increased costs. However, on considering GPS, it can be seen that for about twice the cost of a Loran-C timing receiver, one gets 8-10 times the performance. It should be pointed out that within a few short years, GPS timing receivers have dropped in price from their initial offering of about \$55K to about \$25K in 1985. It is expected that this trend should continue. It is also interesting to note that at \$25K, GPS timing receivers are less than the price of a cesium beam frequency standard. The sub-nanosecond techniques, at this point in time, are still expensive. In order to utilize commercial communication satellites, an Earth station is needed. It would cost about \$105K to outfit one. However, this may not be a significant problem as many laboratories almost have this capability if resources with sister institutions are combined. The use of VLBI requires the equivalent of a radio astronomical observatory. The cost of establishing one would be in excess of \$1000K. A local, high-precision laser ranging system could be established for several hundreds of thousands of dollars. To expand to an intercontinental time transfer system would require the establishment of an observatory quality facility at a cost in excess of a million dollars. However, one should not look at askance at these techniques. It may not be necessary to commit these vast resources to utilize these techniques. Several observatories already participate in VLBI networks. Consequently, the building blocks for nodes in an organized time transfer system exist. As timekeeping capabilities evolve and there becomes a greater need to perform super-precise and accurate time transfers on a regular basis, the use of existing resources in a cost-effective manner will evolve.

DISCUSSION AND CONCLUSIONS

It does not seem that in the next ten years we will have any significant changes in time transfer instrumentation. Existing technology, with improvements, can probably keep up with timekeeping improvements, which will be based upon the introduction of hydrogen maser devices into time scales and also other new standards such as stored ion devices. Unless some serendipitous discovery allows a new type of technology to be applied to timekeeping, there appears to be no major quantum leap in time transfer technology capabilities in prospect. Most likely, we will witness a gradual evolution in the improvement of precision and accuracy of current techniques, some of which are in their developmental stage, i.e., laser-ranging. Most likely, these improvements will lead to the 10-100 ps range in time transfer capability. Satellite communications systems will play a larger role in time transfer techniques. These systems will go to higher frequencies with greater system bandwidths. Hopefully, we will see better pre-launch calibration in order to improve their accuracy. We will probably see the development of an intercontinental laser-ranging time transfer system. In order to utilize resources in a cost-effective manner we will see a developing hierarchy where some laboratories or observatories will become important nodes in an integrated time transfer network.

GPS will play a major role in worldwide time transfer. It will become one of the most cost-effective systems for a majority of users, in spite of the cloud of Selective Availability and Denial of Accuracy which hangs over the community of civilian users. There are effective ways to overcome some shortcomings, perhaps not in real time and perhaps not attaining all of the present day's precision attainable with the Standard Positioning Service. However, it still will be a viable cost-effective system. In the coming decade, there could arise a need for satellite-to-satellite time transfers. This would evolve from a need for the worldwide exchange of data through satellites or be driven by scientific reasons such as interferometry in space. There may be a demand for medium precision time transfer in order to synchronize networks of computers. The future will offer many challenges.

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Table 1

TIMEKEEPING IN BETTER

TIMEKEEPING LABORATORIES

1984	1-100us	Commercial cesium just introduced (HP5060). Crystals start to be phased out.
1974	50-1000ns	High Performance Cesium Beam Tube introduced
1984	5-200ns	Time scale algorithm improved. Improved measurement and control systems. Active hydrogen masers introduced. Laboratory type cesiums being run as clocks.
1994	0.1-5ns	Improved optically pumped Cs tubes Stored Ion Devices Passive Hydrogen masers Cooled active hydrogen masers Robust techniques for algorithms Improved measurement systems

Table 2

RF TECHNIQUES FOR

TIME TRANSFER

	1964	1974	1984	SOURCES OF ERROR
VLF	500us	10us	10us	Variation in propagation path delay due to ionosphere
LF	50us	40us	20us	Variations in propagation path dealy due to ionospheric variations and ground conductivity variations
HF	1ms	0.2ms	0.2ms	Propagation delays
TV	-	100ns	10ns	Atmosphere

Table 3

NAVIGATION SYSTEMS FOR

TIME TRANSFER

	1964	1974	1984	COMMENTS
LORAN-C	5-10us	0.5-5us	40-700ns	Seasonal Term
OMEGA	-	5us	5us	
TRANSIT	500us	25us	3-20us	Dependent on satellite used
GPS	-	100ns	5-40ns	Best results with common view

Table 4

SATELLITE SYSTEMS FOR

TIME TRANSFER

	1964	1974	1984	COMMENTS
GOES	-	50us	30us	Time distribution system
DSCS	-	100ns	50ns	Measurement System limited
Commercial Communication Satellite	1us	10ns	200-600ps	Spread Spectrum PRN modems

Table 5

SPECIAL SYSTEMS FOR

TIME TRANSFERS

	1964	1974	1984	
Portable Clocks	1-5us	30-1000ns	5-500ns	Limited by duration of trip
VLBI	-	150ps(15ns)	60ps(3ns)	Ultimately limted by atmosphere to about 60ps accuracy; values in parenthesis indicate verification
Laser-Ranging			200-600ps	

Table 6

COSTS OF VARIOUS

TIME TRANSFER TECHNIQUES

	Method	Cost for System (Receiver)	Accuracy
1)	GOES	$7K	20us
2)	TRANSIT	$12K	15us
3)	LORAN-C	$10K (receiver) $3K (micro-processor)	40-100ns
4)	Portable Clock	$43K	10-100ns
5)	GPS	$20-32K	5-40ns
6)	Comm. Satellites	$30K (antenna) $15K (PRN Modem) $60K (other electronics)	1ns
7)	VLBI		1ns
8)	Laser Ranging		1ns

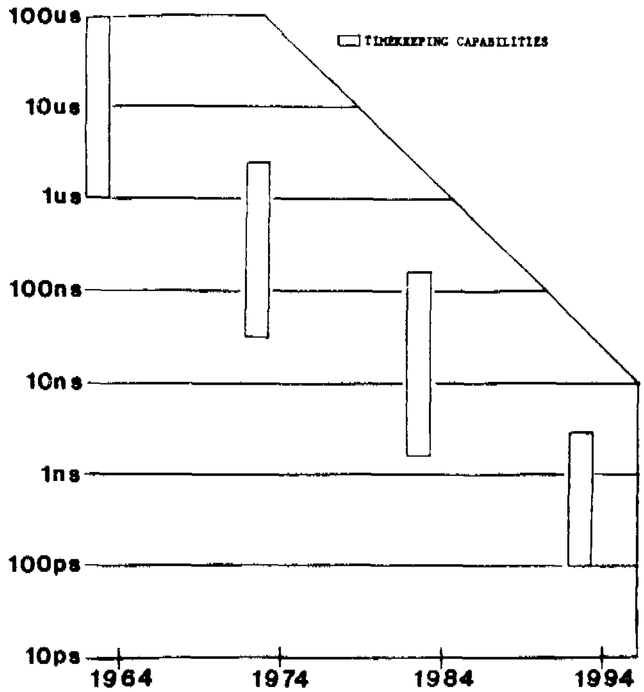

Figure 1 Range of values expected in timekeeping capabilities at better laboratories. The values for 1984 are author's estimates.

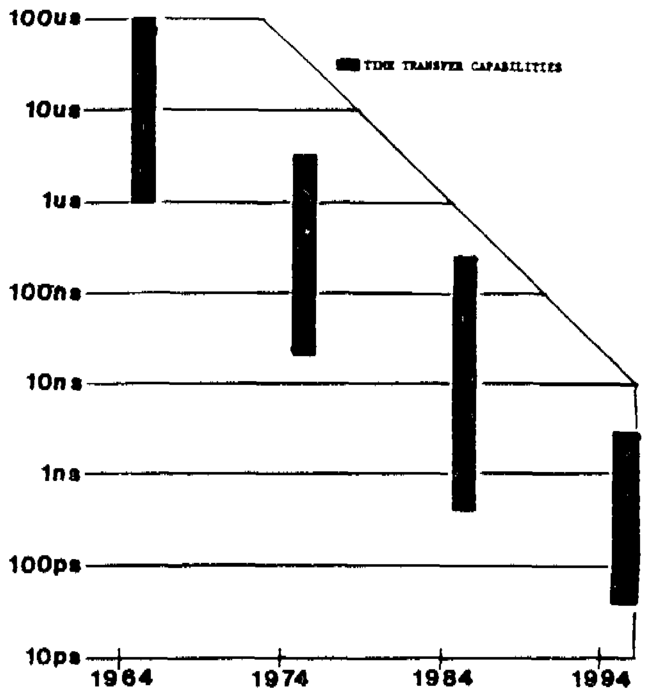

Figure 2 Range of Time Transfer capabilities. The values for 1984 are the author's estimates.

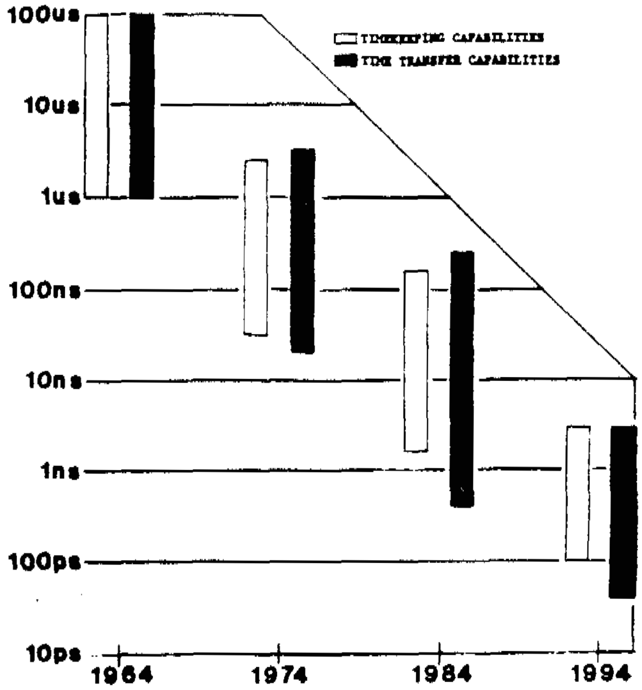

Figure 3 Composite of Figures 1 and 2

QUESTIONS AND ANSWERS

BOB BAKER, VANDENBERG AIR FORCE BASE, FEDERAL ELECTRIC CORPORATION, ITT: Would you say a few words about selective availability for GPS, please.

MR. KLEPCZYNSKI: That is a difficult subject. Right now the plan or policy is that, eventually at some time, when the system becomes operational, the current capabilities of the system for the CA code will be degraded to about a 100 meter precision for navigation purposes, which would mean that it would go down to about 300 nanoseconds for time transfer.

However, the common view mode would eliminate some of these problems.

In addition, not all of the satellites which are in orbit now would have that capability, would not be able to have the selective availability applied to them. It's only the last one or two satellites which have been launched which have that capability, as well as the future ones. Those already in orbit will still provide that capability for five or ten years -- their lifetime. There are some clouds on the horizon, but it's not that bad. The system will evolve and, I think, keep going.

MR. BUISSON: Let me add one thing. The selective availability capability will exist, but there is a chance that it will never happen.

MR. BAKER: Thank you. I have another question: On your commercial satellite, you didn't list the cost of the satellite usage.

MR. KLEPCZYNSKI: That is difficult to get a handle on. Some of the new techniques, in particular the spread spectrum modem, only need one four megahertz wide voice channel. You don't need the number of channels that you need for a TV broadcast or anything like that. Time costs about fifty dollars per hour or less but, for time transfer, you wouldn't be on the air for an hour. All you would have to be on would be five or ten seconds, or maybe five minutes if you wanted it to be really good.

That part of the cost is relatively minor. It's the initial capital cost which would be the biggest problem.

SAM WARD, JET PROPULSION LABORATORY: I think it should be emphasized also that, although highly precise, the laser and VLBI techniques carry a heavy burden in the a priori level of time synchronization that must be established before you can use the technique.

MR. KLEPCZYNSKI: There is no question about it. That's why I indicated that there are going to be very few centers with that capability.